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A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and emissions production: A comparative evaluation

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A B S T R A C T

Global energy demand is increasing due to the population growth and industrialization. In order to fulfill the energy demand with considering global concern, it is necessary to find out alternative fuel sources. Biodiesel is one of the best choices because of its immense potential to be part of energy mix in the near future as well as the capability of reducing greenhouse gas emissions. This paper aims to provide information to the engineers, industrialists and researchers who are interested on biodiesel. The paper presents a comprehensive review on the impact of potential biodiesel feedstocks (edible and non-edible) on engine performance and exhaust emissions including details of engine and operating condition. A large number of literatures from highly rated journals in scientific indexes are reviewed including the most recent publications. Most of the authors showed that using biodiesel from various feedstocks in diesel engines slightly lowered brake power and brake thermal efficiency but increases BSFC than diesel fuel. It was also reported that biodiesel significantly reduced the PM, HC, CO and CO_2 emissions but gives slightly higher NO_x emissions. It was shown that NO_x can be reduced by some approaches such as blending with additives and EGR technique. The study concluded that biodiesel can be used in compression ignition engine with no or minor engine modification. Finally biodiesel can be used as a substitute of diesel fuel to fulfill the energy demand, reduce dependency on fossil fuel as well as the exhaust emissions of the engine.

Contents

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1. Introduction

The global energy map is changing, with potentially far-reaching consequences for energy markets and trade. Global energy demand grows by more than one-third over the period to 2035 with China, India and the Middle East accounting for 60% of the increase. Energy demand barely rises in OECD countries, although there is a pronounced shift away from oil, coal (and, in some countries, nuclear) towards natural gas and renewable. Despite the growth in low carbon sources of energy, fossil fuels remain dominant in the global energy mix, supported by subsidies that amounted to $523 billion in 2011, up almost 30% on 2010 and six times more than subsidies to renewable [1].

Diesel fuel is essential in agricultural, transportation and industrial sector. It contributes to the prosperity of the worldwide economy since it is widely used due to having adaptability, higher combustion efficiency, reliability and handling facilities [2]. However, fossil fuels are limited and their reserves are depleting day by day. On the other hand the emissions from fossil fuel are considered as a major source to the environment pollution [3]. It is predicted, if no enormous efforts are done, that the emissions of greenhouse gases from fossil fuels will increase by 39% in 2030 [4]. That is why many researchers around the world are trying to develop renewable fuels that are domestically available, environmentally acceptable, and technically feasible as well as can fulfill the global energy demand. It has been reported that renewables will become the world's second-largest source of power generation by 2015 (roughly half that of coal) and, by 2035, they approach coal as the primary source of global electricity. The rapid increase in renewable energy is underpinned by falling technology costs, rising fossil-fuel prices and carbon pricing [1].

Biodiesel is considered as an important renewable energy source because of its potential to fulfill the energy demand, reduce greenhouse gasses and global warming [5,6]. Globally, annual biodiesel production increased from 19.6 thousand barrels per day in 2001 to 294.69 thousand barrels per day in 2010. Consumption has also increased from 16.49 thousand barrels per day to 313.77 thousand barrels from 2001 to 2010 [7]. Biodiesel is referred to the fatty acid methyl ester that can be produced from vegetable oils or animal fats by employing pyrolysis, dilution, micro emulsion and transesterification treatment [8–11]. Biodiesel is biodegradable, non-flammable, renewable, non-toxic as well as environment friendly [12–15]. Biodiesel has almost similar properties (such as cetane number, energy content, and viscosity and phase changes) with diesel fuel [16,17]. The major advantages of biodiesel are; it can be blended with diesel fuel at any proportion and can be used in a diesel engine without any modification [18,19]. Moreover, it does not contain any harmful substances and produce less harmful emission to the environment.

Although there are a large number of research papers in last decades on engine performances and emissions characteristics using wide range of biodiesel feedstocks. However, it was observed that only few papers have analyzed and reviewed them [20].

1.1. Objectives of this paper

The main aim of this paper is to provide information to the engineers, industrialists and researchers who are interested on biodiesel. The paper presents a comprehensive review on the impact of potential biodiesel feedstocks (edible and non-edible) on engine performance and exhaust emissions including details of engine and operating condition. A large number of literatures from highly rated journals in scientific indexes are reviewed including the most recent publications.

2. Current biodiesel feedstock

There are more than 350 oil-bearing crops recognized worldwide as potential sources for biodiesel production. The broad range of existing feedstocks for biodiesel production represents one of the most important advantages of biodiesel. According to some researches, feedstock acquisition currently accounts for over 75% of biodiesel production expenses as depicted in Fig. 1. In general, biodiesel feedstocks can be divided into four main categories as below [8,10]:

1. Edible vegetable oil: canola, soybean, peanut, sunflower, palm and coconut oil.
2. Non-edible vegetable oil: *Jatropha curcas*, *Calophyllum inophyllum*, *Moringa oleifera* and *Croton megalocarpus*.
3. Waste or recycled oil.
4. Animal fats: chicken fat, pork lard, beef tallow and poultry fat

Table 1 shows primary biodiesel feedstock for some selected countries around the world. The initial evaluation of the physical

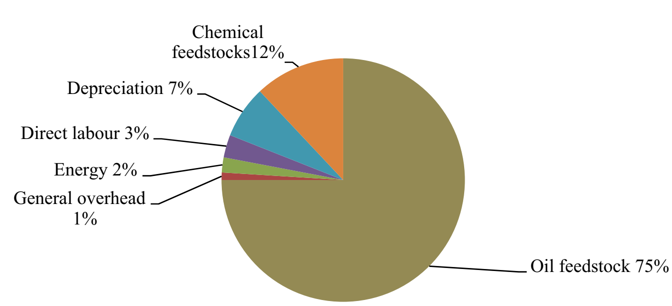

Fig. 1. General cost breakdown for production of biodiesel [8,10,17,23–25].

and chemical properties of edible and non-edible feedstocks is very important to assess their viability for future biodiesel production. Various physical and chemical properties of promising edible and non-edible oil feedstocks can be found literature such as Atabani et al. [21] and Sanford et al. [22].

3. Impact of engine emissions on environment and human health

The emissions which are produced due to combustion of petroleum derived fuel have an adverse effect on environment and human health. It is reported by the unite nation intergovernmental panel that global warming is increasing due to the greenhouse gas emission including methane, nitrogen oxides and carbon dioxides. Liaquat et al. [3] reported that if the average global temperature is increased by more than 2 °C, many people about hundreds of millions of people will lose their lives. Carbon monoxide (CO), hydrocarbon (HC) and formaldehyde (HCHO), Oxides of nitrogen (NO_x), particulate matter (PM) and organic gases other than methane (Non-Methane Organic Gases, i.e. NMOG) which are emitted from internal combustion engine has been identified as harmful to the human health and environment degradation. Table 2 [26–29] shows the impact of exhaust emissions on human health.

Table 1
Current potential feedstocks for biodiesel production worldwide [8].

Country	Feedstock
USA	Soybeans/waste oil/peanut
Canada	Rapeseed/animal fat/soybeans/yellow grease and tallow/mustard/flax
Mexico	Animal fat/waste oil
Germany	Rapeseed
Italy	Rapeseed/sunflower
France	Rapeseed/sunflower
Spain	Linseed oil/sunflower
Greece	Cottonseed
UK	Rapeseed/waste cooking oil
Sweden	Rapeseed
Ireland	frying oil/animal fats
India	Jatropha/*Pongamia pinnata* (karanja)/soybean/rapeseed/sunflower/peanut
Malaysia	Palm oil
Indonesia	Palm oil/jatropha/coconut
Singapore	Palm oil
Philippines	Coconut/jatropha
Thailand	Palm/jatropha/coconut
China	Jatropha/waste cooking oil/rapeseed
Brazil	Soybeans/palm oil/castor/cotton oil
Argentina	Soybeans
Japan	Waste cooking oil
New Zealand	Waste cooking oil/tallow

4. Factors affecting engine emission

Both the regulated and unregulated emissions are affected by the following factors; biodiesel feedstocks (sources); contents of biodiesel, cetane number, advance injection timing and combustion, oxygen contents, engine load, engine speed, density and viscosity. A summary of various reports regarding the factors which have effect on engine emissions such as NO_x, HC, PM and CO has been presented in Table 3.

5. Engine performance and emissions production of various feedstocks

5.1. Palm oil

Ng et al. [85] studied the engine performance using neat palm oil methyl ester, B_{50} and neat diesel (B_0) at different speeds and load conditions. The result showed that SFC for palm oil methyl ester is higher than diesel fuel due to lower energy contents. They also found that neat palm oil methyl ester (B_{100}) reduces tailpipe NO, UHC and smoke opacity by 5.0%, 26.2% and 66.7%, respectively, due to improved combustion, higher cetane number and oxidation of soot. However, it was found that PME content in the fuel blend did not significantly affect tailpipe CO emission, with only a maximum 0.89% reduction achieved with the B_{50}

Table 2
Impact of engine exhaust on human health.

Exhaust emissions	**Impact on health**	**Ref**
PM	Lung cancer and cardiopulmonary deaths	[26]
NO_x	Irritate the lungs and cause oedema, bronchitis and pneumonia; and result in increased sensitivity to dust and pollen in asthmatics	[27]
CO	Its affects fetal growth in pregnant women and tissue development of young children. It has a synergistic action with other pollutants to promote morbidity in people with respiratory or circulatory problems	[27]
HC	Eye irritation, coughing and sneezing, drowsiness and symptoms akin to drunkenness. Some hydrocarbons have a close affinity for diesel particulates and may contribute to lung disease	[27]
PAHs	Eye and nose irritation, coughing, nausea and shortness of breath	[28]
Formaldehyde	Eye and nose irritation, coughing, nausea and shortness of breath	[29]

Table 3
Factors affecting the engine emissions.

Factors	References for NO_x	References for CO	References for PM	References for HC
Biodiesel feedstocks	[30–39]	[30,36,40,41]	[41–43]	[33,36]
Contents of biodiesel	[39,40,43–56]	[44,45,55,57]	[45,51,54,58–60]	[43,54,61]
Higher cetane number	[31,34,43,62,63]	–	[51,64,65]	[66]
Advance injection timing	[35,39,43]	[67–69]	[31,35]	[35,54,67]
Higher oxygen contents	[70]	[48,71,72]	[73]	[74]
Engine load	[31,39,44,46,47,75–77]	[47,71,78–80]	[52,76,81,82]	[31,65,75]
Engine speed	[33,38]	[33,38,83,84]	[64,78]	–

blend. The authors concluded that despite the shortcoming of PME in its higher specific fuel consumption, its overall reduction of regulated tailpipe emissions makes PME green technically viable alternative to fossil diesel in both neat and blended forms for use in light-duty diesel engines

Kalam et al. [86] studied emission and performance characteristics of an indirect ignition diesel engine fuelled with 5% palm (P_5) and 5% coconut oil (C_5) with diesel fuel at constant 85% throttle position. The results show that there are reductions in brake power of 1.2% and 0.7% for P5 and C5, respectively, compared with B_0. This reduction is mainly owed to their respective lower heating values. Compared with B_0, P_5 increases exhaust gas temperature by 1.42% and C_5 decreases it by 1.58%. However, both C_5 and P_5 reduce CO by 7.3% and 21%, respectively, and HC by 23% and 17%, respectively. However, C_5 reduces 1% and P_5 increases 2% of NO_x emission. It was noted that P_5 produces higher CO_2 than C_5 and B_0 fuels. This is mainly the effect of high unsaturated fatty acid in palm oil.

Karavalakis et al. [87] investigated regulated, unregulated exhaust emissions and fuel consumption of diesel fuel and palm based biodiesel blends at proportions of 5%, 20% and 40% (v/v). A Euro 3 compliant light duty vehicle was tested on a chassis dynamometer over the new European driving cycle (NEDC) and the non-legislated Athens driving cycle (ADC). The experimental results showed that the addition of biodiesel increased NO_x emissions. This increase was more significant with the use of B_{20} over both cycles (13.7% and 23.2% over the NEDC and ADC, respectively). Biodiesel addition resulted to increases in CO emissions with the highest increase being 11.78% for B_{20} over NEDC and 11.62% for B_{40} over ADC. HC emissions increased with biodiesel over the NEDC, while over the ADC the addition of biodiesel led to reductions with the highest being with the use of B_{40} (about 26.47%). The same observation holds for PM emissions. Over the ADC the most beneficial reduction was in the order of 50% for the B_{40}. CO_2 emissions and fuel consumption followed similar patterns. B_{20} led to increases up to 6.16% and 2.94% in fuel consumption over NEDC and ADC, respectively. Some PAH compounds demonstrated an increase with biodiesel, while nitro-PAHs decreased with most of them being almost undetectable. Most carbonyl emissions decreased with biodiesel.

Leevijit and Prateepchaikul [88] studied the performance and emission characteristics of IDI-turbo automobile diesel engine operated using degummed, deacidified mixed crude palm oil–diesel blends at various loads and speeds. The test result showed that all blends produce the same maximum brake torque and power. A higher blending portion results in a little higher brake specific fuel consumption (+4.3% to +7.6%), a slightly lower brake thermal efficiency (−3.0% to −5.2%), a slightly lower exhaust gas temperature (2.7% to 3.4%), and a significantly lower amount of black smoke (−30% to −45%). The CO emission of the 20 vol% blend is significantly lower (−70%), and the NO_x emissions of all blends are little higher. The authors concluded that blending of degummed, deacidified palm oil in diesel up to 40 vol% has been found to be satisfactory for short-term usage in the IDI-turbo automotive diesel engine.

5.2. Canola (rapeseed)

Hazar [58] studied the effect of canola oil biodiesel and its blend on a low heat loss diesel engine emission and performance with and without coating condition. The author found out that the increase in power for biodiesel is between 1.6% and 3.5% compared to 8.4% for diesel. While the decrease in SFC for biodiesel is between 4.7% and 8% compared to 4.9% for diesel. There is a significant reduction in exhaust gas emission CO (22–24%) compared to 25% for diesel, and smoke (4.7–8.2%) compared to 9% for diesel. However, NO_x emission increase (4.8–7.3%) compared to 4.9% for diesel. This is attributed to the higher oxygen contents and increase in after combustion temperature due to the ceramic coating. Exhaust gas temperature increases by between 5.4% and 2.6% for biodiesel while it increases by 11.4% for diesel.

Ekrem [76] investigated the performance, emission and combustion characteristics a diesel engine using pure rapeseed biodiesel and 5%, 20% and 70% biodiesel blend at full load. The results show that there are no noticeable differences in the measured engine power output between diesel and B_5 fuels. However, the measured engine power for other blends is lower than that of the diesel fuel. Moreover, the use of biodiesel produces lower CO and smoke opacity and higher BSFC, higher exhaust gas temperatures and NO_x emissions compared to diesel fuel. It was found that B_{20} gives the best brake thermal efficiency of engine. The test results indicated that the only low concentration blends in terms of performance efficiency and environmentally friendly emissions could be recognized as the potential candidates to be certificated for full scale usage in unmodified diesel engines.

Nwafor et al. [89] studied the emission characteristics of a diesel engine at different loads using rapeseed oil methyl ester (RME) and its 25%, 50%, 75% blends. The test results showed that RME and its blends emitted high CO_2 compared to diesel. Moreover, a significant reduction in emissions of hydrocarbon (HC) was recorded when running on RME and the blends. The fuel economy was a little worse when running on RME due to its low energy content. There was no marked difference noted for the exhaust temperatures of the blends.

Karabektas [90] evaluated the effect of turbocharger on the performance and exhaust emissions of naturally aspirated four-stroke direct injection diesel engine at full load condition and speeds between 1200 rpm and 2400 rpm using rapeseed oil methyl ester. The experimental data showed that the brake thermal efficiency and BSFC of biodiesel was slightly higher than that of diesel fuel in both naturally aspirated and turbocharged conditions, while biodiesel yielded slightly lower brake power and torque along with higher fuel consumption values. The NO_x emission with biodiesel is higher than that with diesel fuel, while CO emission is lower for both fuels. The author concluded that the use of biodiesel improves the performance and exhaust emissions of the turbocharged engine better compared with the use of diesel fuel.

5.3. Soybean

Fontaras et al. [49] studied the effect of soybean oil biodiesel and its 50% by volume blend on a Euro 2 diesel passenger car. The result showed that biodiesel fuel increased SFC. For instance B_{50} increased SFC by 9% and 4.5% over the NEDC and Artemis driving cycles due to the lower energy contents in biodiesel fuel. Moreover, use of B_{50} and B_{100} led to CO increases over NEDC in the order of 54% and 95%, respectively. B_{50} and B_{100} increase HC emissions by 31% and 58%, respectively, over the NEDC cycle. B_{50} leads to equal or slightly lower NO_x emissions than petroleum diesel. However, B_{100} leads to higher NO_x emissions in the range of 6–9%. Use of the biodiesel reduced solid particle population but significantly increased the total particle number. The results indicated that maximum engine power output decreased as the biodiesel concentration increased. The authors concluded that biodiesel at high blending ratios may strongly impact emissions, in a rather non-uniform manner, with the actual effect being dependant on driving conditions and blending ratio. However this study does not reach definitive conclusions but rather presents a case that may appear in the European passenger car fleet, which requires further attention and research.

Qi et al. [91] studied the combustion and performance characteristics of a direct injection engine fueled with biodiesel from soybean oil and its different blend (B_0, B_{30}, B_{50}, B_{80}, B_{100}). The test result showed a small increase in BSFC for biodiesel and its blends due to the lower heating value of biodiesel. The BTE of biodiesel and its blends are slightly lower than that of diesel at low engine loads keeping the same trend to the higher engine load. The significant improvement in reduction of carbon monoxide (CO) and smoke were found for biodiesel and its blends at high engine loads. HC emissions of biodiesel and its blendes have little difference from diesel fuel. Nitrogen oxides (NO_x) were slightly higher for biodiesel and its blends. This is because of the increases the combustion chamber temperature due to higher oxygen content in biodiesel. The authors concluded that the excess oxygen contents of biodiesel play a key role in engine performance and biodiesel is proved to be a potential fuel for complete or partially replacement of diesel fuel.

Armas et al. [67] investigated the effect of alternative fuel on engine emission using three types of fuel: an ultra-low sulfur diesel fuel (BP15), a pure soybean methyl-ester biodiesel fuel (B_{100}) and a synthetic Fischer–Tropsch fuel (FT). The BSFC for B_{100} is approximately 15% higher than for BP15 while the brake efficiency for B_{100} is about 8% lower than for BP15. With B_{100}, the NO_x emission is about 16.7% lower than for BP15. HC emissions for B_{100} are about 12% lower than for BP15 but higher than (FT), while CO emissions for B_{100} are about the same level as for BP15. However, the highest PM mass emission for B_{100} has been observed under the condition of matched combustion phasing. The increase of the PM mass emission is probably due to the unburned or partially burned hydrocarbon (HC) emissions.

5.4. Sunflower

Ulusoy et al. [78] studied the emission characteristics of a 4 stroke turbo diesel engine with 4 cylinders, direct injection using sunflower oil methyl ester at different speeds and full load condition. The result showed that smoke HC and CO emissions of sunflower oil methyl ester are generally lower than diesel fuel for all engine speeds. The test engine's turbocharger mechanism and oxygen content of biodiesel fuel have caused emission values to be lower by increasing the combustion quality. The authors concluded that biodiesel's exhaust emissions are lower than diesel fuels, which indicates that biodiesel has more favorable effects on air quality.

5.5. Mahua (Madhuca indica)

Godiganur et al. [50] studied the performance and emission characteristics of a Cummins 6BTA 5.9 G2-1, 158 HP rated power, turbocharged, DI, water cooled diesel engine using diesel fuel, mahua oil methyl ester and its blend at different load and constant speed (1500 rpm). The test results showed that increasing proportion of biodiesel in the blends significantly reduces CO and HC emissions due to the complete combustion of biodiesel. However, NO_x emissions increased slightly (11.6%) when compared with that of pure diesel. This could be attributed to the increased exhaust gas temperatures and the fact that biodiesel had some oxygen content in it which facilitated NO_x formation. The BSEC for B_{20} was observed lower than diesel. In case of B_{40}, B_{60}, and B_{100}, the BSEC was higher than that of diesel. This reverse trend was observed due to lower calorific value with increase in biodiesel percentage in the blends. The maximum thermal efficiency for B_{20} (32.5%) was higher than that of diesel. The brake thermal efficiency obtained for B_{40}, B_{60} and B_{100} were less than that of diesel. This lower brake thermal efficiency obtained could be due to the reduction in calorific value and increase in fuel consumption as compared to B_{20}. There is a small reduction in BSEC (brake specific energy consumption) and slightly increase in BTE (thermal efficiency) of engine compared to diesel fuel was observed when it was run on 20% biodiesel. The exhaust gas temperature was found to increase with the increasing concentration of biodiesel in the blends. The mean EGTs of B_{20}, B_{40}, B_{60} and B_{100} were 7%, 9% 10% and 12%, respectively, higher than the mean EGT of diesel. This could be due to the increased heat loss of the higher blends, which are also evident from, their lower brake thermal efficiencies as compared to diesel. From these findings, it is concluded that mahua biodiesel could be safely blended with diesel up to 20% without significantly affecting the engine performance (BSFC, BSEC, EGT) and emissions (CO, HC and NO_x) and thus could be suitable alternative fuel for heavy-duty engines.

Puhan et al. [63] compared the performance and emission of a single cylinder, four stroke direct injection constant speed compression ignition diesel engine (Kirloskar) using biodiesel from mahua oil. The result showed that the performance of diesel engine with biodiesel does not vary significantly. The specific fuel consumption is higher (20%) than that of diesel and thermal efficiency is lower (13%) than that of diesel. Exhaust pollutant emission are reduced compared to diesel. Carbon monoxide (CO), hydrocarbon (HC), smoke number, oxides of nitrogen (NO_x) were reduced 30%, 35%, 11%, 4%, respectively, compared to diesel. The most interesting finding of this study is that oxides of nitrogen reduced even though that Nitrogen oxide is reported by several researchers to be increased with biodiesel.

Puhan et al. [74] studied the performance and emission of mahua oil ethyl ester (MOEE) in a 4-stroke natural aspirated direct injection diesel engine. Tests were carried out at constant speed of 1500 rev/min at different brake mean effective pressures. The result showed that the average reduction in carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and Bosch smoke number were 58%, 63%, 12% and 70%, respectively, in case of MOEE compared to diesel. However, the results show that a carbon dioxide (CO_2) emission and BSFC from MOEE is greater than diesel. The maximum brake thermal efficiency of mahua oil ethyl ester (MOEE) was comparable with diesel and it was observed that 26.36% for diesel whereas 26.42% for MOEE at 5.481 BMEP. This small variation of thermal efficiency may be due to the chemical composition of MOEE, which promotes the combustion process. The highest value of exhaust gas temperature of 439 °C was observed for MOEE, whereas for diesel it was found to be 249 °C only.

Saravanan et al. [92] investigated the performance and emission of a diesel engine fuelled with *Madhuca indica* biodiesel. Experiments were conducted on a single cylinder, four stroke, air cooled, direct injection, compression ignition engine using mahua oil methyl ester and diesel as fuel. The result showed that at full load, the power loss was around 13% combined with 20% increase in fuel consumption with mahua oil methyl ester due to the lower heating value and higher viscosity of biodiesel fuel. Emissions such as carbon monoxide, hydrocarbons were lesser for mahua ester compared to diesel by 26% and 20%, respectively, due to the higher oxygen contents which promoted combustion. Oxides of nitrogen were lesser by 4% for the ester compared to diesel due to the lower in cylinder temperature. A smoke intensity reduction of 15% for MOME was also observed at full load. It was also observed that the exhaust gas temperature for MOME operation is lower compared to that of diesel.

5.6. Karanja (Pongamia pinnata L.)

Baiju et al. [30] evaluated the performance and exhaust emission characteristics using petro diesel as the baseline fuel and several blends of diesel and biodiesel from karanja oil in a diesel engine. The result showed that engine performance does not differ

greatly than diesel fuel. A little power loss, lower BTE and higher BSFC was observed due to lower heating value of ester than with diesel. It was also observed that the methyl esters produced slightly higher power and lower emissions than ethyl esters. They also found the NO_x emissions increase by 10–25% when fuelled with diesel–biodiesel fuel blends as compared to conventional diesel fuel at part loads. At full load, diesel emits more NO_x than esters and most of the major exhaust pollutants such as CO, HC and smoke are reduced with the use of neat biodiesel and the blends. The study concluded that both methyl and ethyl esters of karanja oil can be used as a fuel in compression ignition engine without any engine modification

Nurun Nabi et al. [52] studied the effect of karanja (*Pongamia pinnata*) biodiesel on exhaust emission of a diesel engine and compared with the diesel fuel. They authors reported that compared to DF, B_{100} reduced carbon monoxide (CO) (50%), smoke (43%) and engine noise (2.5 dB). However, an increase in oxides of nitrogen (NO_x) of 15% was reported at high load conditions. The reason for reducing CO, smoke and engine noise and increasing in NO_x emission is due to the presence of oxygen in karanja biodiesel molecular structure. Moreover, low aromatics in the B_{100} and its blends may be an additional reason for reducing these emissions. The authors also reported that compared to DF the brake thermal efficiency with B100 and its blends was almost unchanged.

Raheman and Phadatare [59] studied the emission and performance of a diesel engine using karanja oil methyl ester (KME) blends B_{20}–B_{100} and compared with diesel fuel. They found out that as compared to diesel, B_{20}–B_{100} blends resulted in a reduction of maximum 94% and minimum 73% of CO emissions, maximum 80% and minimum 20% of smoke density and 26% in average NO_x emission. The reason of reducing all the emissions is the complete combustion of the biodiesel blend fuel. The exhaust temperature measured varied between 260 °C and 336 °C as compared to 262 °C and 335 °C for diesel indicating no much variation in exhaust temperature. The brake power output increased on an average 6% up to biodiesel blend B_{40} and with a further increase in the biodiesel percentage in the blend it reduced. They also reported that B_{20} and B_{40} gives 0.1–13% higher torque than diesel fuel due to complete combustion; in case of B_{60}–B_{100} it reduced torque by 4–23% due to the decreasing calorific value with increasing the percentages of biodiesel in the blend. On the other hand, for an average speed B_{20}–B_{40} lowered BSFC 0.8–7.4% than diesel fuel but B_{60}–B_{100} give 11–48% higher BSFC. This is attributed to the lower calorific value of the biodiesel fuel. The authors concluded that the blends of karanja methyl ester with diesel up to 40% by volume could replace diesel for running the diesel engine for getting less emissions without sacrificing the power output and will thus help in controlling air pollution to a great extent.

5.7. Cottonseed

Aydin and Bayindir [55] analyzed the performance and emission characteristics of cottonseed oil methyl ester (CSOME) and its 5%, 20%, 50%, 75% blends in a diesel engine at various engine speeds and full load condition. Fuels were tested in a single cylinder, direct injection, air cooled diesel engine. The results showed that at lower engine speed the BSFC of B_{20} were observed lower than those of other fuels including diesel fuel. It may be due to the fuel based oxygen and higher cetane number, leading to more complete combustion at low speeds. While at higher speeds (2000 rpm) the minimum BSFC were observed for D_2, B_5 and B_{20} fuels. It may be due to the combined effect of higher viscosity and lower calorific value of the blend than those of diesel engine. It was also observed that the torque was decreased as CSOME increase in the blends. This is most likely is attributed to the higher viscosity and lower heating value of CSOME. As for B_5, the torque was obtained slightly higher than other fuels including D_2. The highest value of exhaust gas temperature was observed at 2500 rpm with diesel fuel. While at lower engine speed the higher exhaust gas temperatures were obtain for B_{75} and neat CSOME. The CO and SO_2 emissions decreased with increasing biodiesel percentage. In contrast to many researchers, the NO_x emission was decreased for all blends and B_{100} except for B_5 in these experiments. The experimental results concluded that the lower contents of CSOME in the blends can partially be substituted for the diesel fuel without any modifications in diesel engines

Nurun Nabi et al. [93] studied the effect of cottonseed oil biodiesel on engine performance and emission. It was found that thermal efficiency of biodiesel fuel was lower than that of diesel fuel due to the poor spray characteristics, higher density, viscosity and lower heating value of biodiesel fuel. The emissions of CO, PM and smoke from biodiesel was less than those of neat diesel fuel. However, NO_x emission with biodiesel mixtures was higher compared to neat diesel fuel. For instance, with 10% biodiesel mixtures (B_{10}) PM and smoke emissions reduced by 24% and 14%, respectively. While biodiesel mixture of 30% (B_{30}) reduced CO emissions by 24% and NO_x emissions increased by 10%. The authors attributed the reduction in PM, smoke and CO emissions and increase in NO_x emission with biodiesel mixtures to the presence of oxygen in their molecular structure as well as low aromatics in the biodiesel blend.

5.8. Jatropha curcas

Chauhan et al. [94] evaluated the performance and exhaust emissions using 5%, 10%, 20% and 30% jatropha biodiesel blends with diesel fuel on an unmodified diesel engine. The experimental results show that engine performance with biodiesel of jatropha and its blends were comparable to the performance of diesel fuel. In case of all fuel blends, brake thermal efficiency, HC, CO, CO_2 and smoke density were lower while BSFC and NO_x were higher than that of diesel. The authors concluded that biodiesel derived from jatropha and its blends could be used in a conventional diesel engine without any modification. However there are various parameters which can be evaluated in future such as the prediction of best blend with respect to the various engine parameters by varying spray time of fuel using common-rail fuel injection.

5.9. Tobacco

Usta [71,46] evaluated the performance and exhaust emissions of a turbocharged indirect injection diesel engine using 10%, 17.5% and 25% tobacco seed oil methyl ester blend (TSOME). The author found that the addition up to 25% in volume of TSOME did not cause any significant variation in the engine torque and power. Although the heating value of the TSOME is 10.8% less than that of the diesel fuel. Moreover, it was found that the blending of tobacco seed oil methyl ester to the diesel fuel reduced CO due to the fact that TSOME contains about 11.4% oxygen by weight and SO_2 emissions due to low sulphur content while causing slightly higher NO emissions due to higher combustion temperature.

5.10. Polanga (Calophyllum inophyllum)

Sahoo et al. [56] evaluated the performance and emission of polanga oil methyl ester (POME) blends (0–100%) in a single cylinder diesel engine at different loads (0–100%). The main findings of the study showed that the performance of biodiesel-fueled engine was marginally better than the diesel-fueled engine in terms of thermal efficiency, brake specific energy consumption, smoke opacity, and exhaust emissions including NO_x emission for entire range of operations. The 100% biodiesel was found to be the

best, which improved the thermal efficiency of the engine by 0.1%. Similar trend was shown by the brake specific energy consumption and the exhaust emissions were reduced. Smoke emissions also reduced by 35% for B_{60} as compared to neat petro-diesel. Decrease in the exhaust temperature of a biodiesel-fueled engine led to approximately 4% decrease in NO_x emissions for B_{100} biodiesel at full load. It was conclusively proved that excess oxygen content of biodiesel played a key role in engine performance. However long term endurance test and other tribological studies need to be carried out before suggesting long term application of polanga oil based biodiesel.

5.11. Eruca Sativa Gars (ESG)

Li et al. [95] studied the performance and emission of a diesel engine fuelled with biodiesel from Eruca Sativa Gars (ESG) oil. The engine test was tested in a truck named Fukuda light truck BJ1043V8JE6-2 of which engine model is CY4100Q. The fuels were tested at different loads where the engine torques were in the range of 200–2000 N m. At this range, the fuel consumption rates of B_{100} are higher from 8% to 18%. B_{20} and B_{50} exhibit higher fuel consumption rate from 1% to 8% and 5% to 11%. CO emissions for B_{100}, B_{50}, B_{20} and B_{10} were less than diesel. The UHC emissions for B_{100}–B_{10} reduced from 33 to 0%. It was observed that with a higher content of biodiesel, the smoke emissions decreases while NO_x emissions increases. The authors suggest that B_{10} does not affect the engine combustion efficiency.

5.12. Terebinth

Özcanli et al. [96] studied engine performance and emission on a three-cylinder, four stroke, and direct-injection CI engine operated with terebinth oil biodiesel and its 5%, 10%, 20% and 50% by volume blends at full load condition. The results of engine performance indicated that power values of blends showed a trend of decreasing depend on content of biodiesel at higher engine speeds. The maximum reduction ratio was 6.18% with B_{100} at 2400 rpm. The average rates of increases in SFC were 2.59% with B_{25}, 3.86% with B_{50}, and 5.62% with B_{100}. The results are mainly due to higher density and lower calorific value of blend fuels. According to the emission analysis, the average rates of decreases in CO emission were 12.50% with B_{25}, 18.33% with B_{50}, and 22.91% with B_{100}. However, NO_x emissions with B_{25}, B_{50}, and B_{100} showed a trend of increasing. The maximum NO_x emission increase ratio of 32.97% was obtained with B_{100} at 2200 rpm. The CO_2 emissions of B_{25}, B_{50}, and B_{100} were lower than those of diesel at all engine speeds. It was observed that the maximum reduction of CO_2 was 10.69% with B_{50} at 1800 rpm.

5.13. Rubber

Ramadhas et al. [97] evaluated the engine performance and emissions of a diesel engine fueled with methyl esters of rubber seed oil. Their results showed that the maximum brake thermal efficiency obtained is about 28% for B_{10}, which is quite higher than that of diesel (25%). Moreover, it was observed that using lower percentage of biodiesel in biodiesel–diesel blends, the brake specific fuel consumption of the engine is lower than that of diesel for all loads. Under all loading conditions, it was observed that the engine emits more CO using diesel as compared to that of biodiesel blends. However, using higher concentration of biodiesel blends increase CO_2 and NO_x emission. Smoke density for biodiesel blend is noticed to be generally lower than that of diesel. For instance, B_{20} blends gave smoke density of 28% as compared to 45% in the case of diesel. The experimental results proved that the use of biodiesel produced from unrefined rubber seed oil in compression ignition engines is a viable alternative to diesel.

Pradeep and Sharma [98] presented the performance, emission and combustion parameters of a single cylinder diesel engine running on biodiesel from rubber seed oil and its diesel blends (B_{20}, B_{60} and B_{80}) with diesel. They found that brake thermal efficiencies were lower for biodiesel blends compared to diesel. Higher combustion duration and lower heat release rates were also recorded for biodiesel.

5.14. Desert date

Chapagain et al. [99] studied the performance and emission characteristics of a diesel engine operated with desert date biodiesel using B_{100} (100% desert date biodiesel), B_5 (5% blend) and B_0 (0%biodiesel) at different rpm (1200–2200). A small reduction of approximately 2% in fuel consumption was obtained using neat biodiesel compared to diesel. Power output of the engine was reduced by approximately 4% using B_{100} compared to diesel. Emission of nitric oxide was reduced by approximately 6% using neat Desert date biodiesel compared to diesel. Further reduction of NO was found in the 5% blend. With the use of biodiesel, emissions were reduced 60% and 68% compared to diesel for CO and HC, respectively.

5.15. Fish oil

Mrad et al. [100] studied the effect of fish oil industrial residue biodiesel and its blend on diesel engine performance and emission. The experimental results show that the brake thermal efficiency increases from 29.98% with neat diesel to 30.6% with B_{20}, 31.1% with B_{40} and the maximum of 32.4% with B_{100} at 80% of maximum load. At maximum load, the value of exhaust gas temperature for biodiesel and diesel is 422 °C and 495 °C, respectively. The HC and CO emissions for diesel, B_{20} and B_{40} is 575 ppm and 0.59%, 561 ppm and 0.54% and 536 ppm and 0.48%, respectively, at maximum load which shows biodiesel blends produces less HC and CO emissions compared to diesel. The PM emissions decrease when the percentage of biodiesel increases in the blend. The NO_x emissions at 80% of maximum load are 917 ppm with biodiesel, 852 ppm with diesel, 882 ppm with B_{40} and 866 ppm with B_{20} blend. These results indicate that there is a slight increase in NO_x emissions with biodiesel and its blends than diesel. The authors concluded that the biodiesel from fish oil industrial residue by catalytic cracking can be the substitute for diesel fuel.

Lin and Li [33] studied the performance and emission of marine fish oil biodiesel fuelled diesel engine and compared it with waste cooking oil biodiesel and diesel fuel. The main findings of this study showed that the marine fish-oil biodiesel was found to have higher exhaust gas temperature, NO_x, CO and O_2 emissions, black smoke opacity and a lower (BSFC). However, in comparison with the ASTM No. 2D diesel, both marine fish oil biodiesel and waste cooking oil biodiesel were shown to have a higher BSFC, NO_x, CO and O_2 emissions and black smoke opacity.

Godiganur et al. [48] studied the performance and emission characteristics of biodiesel from fish oil and its blend in a Kirloskar H394 DI diesel engine, at constant speed of 1500 rpm under variable load conditions. The result indicated that BSFC for neat biodiesel (B_{100}) is higher than the diesel fuel. However, the BSFC and BSEC of B_{20} were lower than the diesel and all other fuel. The maximum thermal efficiency for B_{20} (31.74%) was higher than that of diesel (30.78%). The brake thermal efficiency obtained for B_{40}, B_{60}, B_{80} and B_{100} were less than that of diesel. The exhaust temperature increased as a function of the concentration of biodiesel blend. This increased lead to increase in NO_x emissions

for biodiesel blends. The biodiesel blended fuel lowered the HC and CO emission due to complete combustion.

Swaminathan and Sarangan [101] studied the effect of fish oil biodiesel (BFO) blended with oxygenate and EGR technique in a single cylinder diesel engine to improve the performance and reduce the emission of the engine. It has been found that CO, CO_2 and C_xH_y emissions were reduced when using BFO compared to diesel. However, an increase of about 48% of NO_x was obtained at maximum load when using BFO compared to diesel. The addition of additive and EGR technique reduced NO_x emission. The optimum value of additive was 2%. Using BFO with 2% additive and EGR has resulted in a reduction of CO, $CO_{2,}$ NO_x and $C_xH_y$of 91%, 62%, 92% and 90%, respectively, when the engine was run at maximum load. Same observation was drawn when the engine was run in other loads.

5.16. Jojoba

Saleh [102] studied the performance and exhaust emissions of a two-cylinder, naturally aspirated, four-stroke direct injection diesel engine operating with diesel and Jojoba methyl ester (JME). This was followed by studying the effect of exhaust gas recirculation (EGR). The result showed that the engine power and brake thermal efficiency with JME are slightly higher than the diesel. The BSFC with JME is lower (8.2–9.8%) than that of diesel. Author also found that JME also give higher concentration of NO_x of 14% at 1600 rpm and 16% at 1200 rpm. At lower engine speed JME produce higher HC and CO emissions. At high speed, there is no appreciable difference between HC concentration with JME and diesel fuel while CO of JME is lower than diesel. The results also showed that when the EGR rate is increased, the NO_x emissions decreased. However, CO and HC emissions increased. The optimum EGR level is 5–15% for all engine speeds and loads and that may be favorable in a trade-off between HC, CO and NO_x emissions with little economy penalty.

5.17. Rice bran

Saravanan et al. [103] studied the feasibility of crude rice bran oil methyl ester (CRBME) in diesel engine. The result showed that, with CRBME blend the brake thermal efficiency decreases only marginally due to the lower heating value of the methyl ester. Moreover, a significant reduction in CO, UBHC and particulate emission were observed with a marginal increase in NO_x emission than that of diesel due to higher oxygen contents of methyl ester.

5.18. Neem

Nabi et al. [104] studied emission characteristics of a four stroke naturally aspirated (NA) direct injection (DI) diesel engine using Neem oil methyl ester (NOME). They found lower carbon monoxide (CO), and smoke emissions but higher oxides of nitrogen (NO_x) emission in case of using biodiesel–diesel blends compared to diesel. The reason of lowering all emissions is associated with the higher oxygen contents in biodiesel. On the other hand, compared with diesel, NO_x emission with diesel–biodiesel blends was slightly reduced when EGR was applied.

Sharma et al. [105] studied the performance and emissions of a direct injection diesel engine fueled by Neem-diesel blend. They reported that neem biodiesel gives slightly lower brake thermal efficiency (BTE) and higher brake specific fuel consumption (BSFC) than diesel at all loads. A significant reduction in the NO_x, smoke density, CO and unburned hydrocarbon (UHC) emissions with compare to diesel fuel was observed.

5.19. Leather industry pre-fleshings

Özgünay et al. [34] studied the performance and emission of biodiesel from leather pre-fleshings in a diesel engine. The test results demonstrated that power and BSFC with biodiesel were 1.3% and 0.8% lower than diesel due to lower calorific value of the fuel. The emission values of carbon monoxides (7.5%), hydrocarbons (20%) and particulate matter (62.6%) were lower with biodiesel compared to diesel fuel. However, NO_x and CO_2 emissions were 2.2% and 3.5% higher than diesel.

5.20. Apricot (Prunus armeniaca)

Gumus and Kasifoglu [47] evaluated the performance and emission characteristics of a diesel engine using apricot seed kernel oil methyl ester (ASKOME) and its blend. Lower percent of ASKOME blends (B_5, B_{20}) give a good improvement in the engine power. Furthermore they were found to improve exhaust emissions. Higher percent of ASKOME blend (B_{50}) and neat ASKOME reduced CO, HC emission and smoke density effectively. This can be attributed to the higher oxygen contents in biodiesel which results more completed combustion. However, they increased slightly NO_x emission and give lower performance characteristics than diesel fuel. Therefore, lower percent of ASKOME can be used as additive, which improves performance and exhaust emission in diesel fuel.

5.21. Pistacia chinensis Bunge

Zhihao et al. [106] studied the emission characteristics of a diesel engine fuelled with *Pistacia chinensis* Bunge seed biodiesel blend. The result showed that CO, HC and exhaust smoke emissions decrease with the increase of the proportions of biodiesel in the blends due qto the higher oxygen contents and absence of sulphur in the blend. The NO_x emissions are reduced as the engine operating with B_{10} and B_{20}, but slightly increased with B_{30} due to the higher oxygen contents which increases the in cylinder temperature.

5.22. Sal (Shorea robusta)

Vedaraman et al. [107] studied the performance and emission of a diesel engine operated using sal oil methyl ester (SOME). The result showed that using sal oil biodiesel reduces exhaust emission such as CO (45%), HC (55%) and NO_x (12%) compared to diesel fuel due to cetane number, absence of sulphur and higher oxygen contents in biodiesel fuel. However, the CO_2 emission for SOME is high when compared to diesel. This is because the ester-based fuel burns efficiently compared to diesel. They also found that there is no significant difference in brake thermal efficiency of biodiesel with diesel fuel. But it gives higher BSFC compared to diesel fuel. However, they concluded that biodiesel from sal oil can be used in a diesel engine with no modification.

5.23. Waste cooking oil

Mumtaz et al. [108] studied the diesel engine emission using waste cooking oil biodiesel from (WCOB) and its 5%, 20%, 40%, 50% and 80% by volume blend. The main findings of their study revealed the average reduction in CO emissions increased from −7.3% for WCOB-5 to −61.82% for WCOB-100. For PM the average reduction increased from −3.17% for WCOB-5 to −54.26% for WCOB-100. However, it was observed that NO_x increase from −1.67% for WCOB-5 to +4.6% for WCOB-100. The authors concluded that WCOB-20 was revealed as an efficient WCOB blend with reasonable reduction in CO, PM, and NO_x emissions.

Hirkude et al. [109] conducted the performance and emission test of a diesel engine fuelled with waste fried oil methyl ester

(WFOME) and its blend. The experiment was conducted in a single-cylinder, four-stroke, direct injection, diesel engine. The results indicated that the performance parameters for different WFOME blends were found to be very close to diesel and the emission characteristics of engine improved significantly. The brake thermal efficiency decreased with increase of WFOME in the blend. The brake thermal efficiency of B_{50} was found 6.5% lower than that of diesel. The specific fuel consumption increased with increase of WFOME in the blend. For B_{50}, brake specific consumption observed was 6.89% higher than that of diesel. The exhaust gas temperature increased with increase of WFOME in the test fuel for all the loads. The highest exhaust gas temperature observed was 309 °C for B_{90} and the lowest, 291 °C for mineral diesel. CO emissions were reduced by 21–45% for different blends. The particulate matters were lower by 23–47%. Because of insignificant sulfur content, the sulfur dioxide emissions were lower by 50–100% for different blends. NO_x emission was higher by 4–10% with increase in WFOME concentration.

Lin et al. [110] investigated the performance and emission of heavy duty diesel engine operated using waste cooking oil biodiesel blend (B_5, B_{10}, B_{20}, and B_{30}) and compared with ultra-low sulphur diesel (ULSD). The result showed that biodiesel blend lowered the PAHs (7.53–37.5%), PM (5.29–8.32%), HC (10.5–36%), and CO (3.33–13.1%) emissions compared to ultra-low sulfur diesel (ULSD) fuel due to the higher oxygen contents. BSFC was higher for biodiesel blends as a consequence of biodiesel having a lower heating value.

Utlu and Koçak [111] investigated the effect of biodiesel from waste frying oil methyl ester (WFOME) in a diesel engine with turbocharged, four cylinders and direct injection. Due to the lower heating value, higher viscosity and density WFOME's fuel consumption is 14.34% higher and power is 0.55% lower than diesel fuel. Average decrease of torque values was 4.3% for WFOME. The average emissions reduction was determined as 17.14% for CO, 1.45% for NO_x and 8.05% for CO_2. Smoke intensity is increased in average 22.46% for the utilization of WFOME compared to diesel fuel. Exhaust temperatures of WFOME is decreased on average 6.35% than diesel fuel. Therefore, Waste frying oil methyl ester can be used cheaply and as an alternative fuel in a diesel engine instead of diesel fuel.

Meng et al. [57] tested the impact of biodiesel from waste cooking oil on an YC6M220G turbo-charge diesel engine performance and emissions. The testing results show that B_{20}, B_{50} blend fuels (include 20%, 50% crude biodiesel, respectively) led to unsatisfactory emissions whilst the B'_{20} blend fuel (include 20% refined biodiesel) reduced significantly particles, HC and CO emissions. For example CO, HC and particles were reduced by 18.6%, 26.7% and 20.58%, respectively, compared to diesel.

Kannan et al. [112] studied the performance and emission of a diesel engine using ferric chloride ($FeCl_3$) as an additive with waste cooking palm biodiesel at constant speed of 1500 rpm and different load condition. The results revealed that compared to biodiesel without additive, the additive added biodiesel resulted in a decreased brake specific fuel consumption (BSFC) of 18.4% whiles the brake thermal efficiency increased by 1.8% at 280 bar and 25.5° bTDC condition. Additive added biodiesel showed lower nitric oxide (NO) emission and slightly higher carbon dioxide (CO_2) emission (6.7%) than that of biodiesel without additive. They also found that additive added biodiesel decreased Carbon monoxide (CO), total hydrocarbon (THC) and smoke emission by 52.6%, 26.6% and 6.9%, respectively, at an optimum operating condition of 280 bar injection pressure and 25.5° BTDC injection timing.

5.24. Beef tallow

Selvam and Vadivel [113] studied the performance and emission of a diesel engine using beef tallow biodiesel (B_{100}) and its blend (B_5, B_{25}, B_{50}, B_{75}) with diesel blend at different load condition and constant speed of 1500 rpm. The test result indicates that blended fuels give a slight decrease in BTE and increase in BSFC compared to that of diesel fuel due to the higher density and lower heating value of biodiesel fuel. The emission analysis shows a radical reduction in carbon monoxide (CO), unburned hydrocarbon (UHC) and smoke density for all biodiesel blended fuel due to the higher oxygen contents in biodiesel fuel. The maximum reduction in CO, HC and smoke emission with neat biodiesel are 24.7%, 32.5% and 63%, respectively. However, in the case of oxides of nitrogen, there is a slight increase for all the blended fuels and with neat biodiesel (6.35%) compared to diesel fuel. The authors concluded that methyl esters of beef tallow and its blends with diesel fuel can be used as an alternative fuel for diesel in direct injection diesel engines without any significant engine modification.

5.25. Various studies

Sahoo et al. [40] studied the performance and emission characteristics of jatropha (*J. curcas*), karanja (*P. pinnata*) and polanga (*C. inophyllum*) oil based biodiesel blends (Diesel, B_{20}, B_{50} and B_{100}) in a water-cooled three cylinder tractor engine. The test was run under full/part throttle position for different engine speeds (1200 rev/min, 1800 rev/min and 2200 rev/min). The main findings during full throttle engine performance test showed that the maximum increase in power is observed for JB_{50} at 2000 rpm and 2100 rpm. The maximum increase in BSEC (20.21% higher than that of diesel) is observed in case of JB_{100} at 1200 rpm. Best BSEC is observed with PB_{20} fuel. The maximum reduction in smoke emission was seen in case of KB_{100} (68.83%) and PB_{100} (69.48%) at 2200 rpm. During part throttle performance test, it was observed that the best brake specific fuel consumption improvement is observed with JB_{20} while the least level of smoke emission is observed in case of JB_{100}.

Bakeas et al. [114] studied the impact of biodiesel blends (10–30% v/v) on PM, HC and CO emissions. The biodiesel fuels were a soy-based methyl ester produced from soybean oil blended with palm oil (SMEP), an animal fat methyl ester (AFME), a used frying oil methyl ester (UFOME), and an olive oil methyl ester (OME). A 2007 model year Hyundai i-10, equipped with a common-rail direct injection diesel engine and meeting Euro 4 emission standards, was used in this study. The use of biodiesel had limited effects on CO_2 emissions. Fuel consumption increased with the increase in biodiesel content. PM, HC and CO emissions improved with the addition of biodiesel, with some exceptions. NO_x emissions were increased with the use of biodiesel blends and positively correlated with fuel unsaturation levels.

Performance and combustion characteristics of a direct injection (DI) diesel engine fueled with biodiesels from waste (frying) palm oil methyl ester (WPOME) and canola oil methyl ester (COME) was studied by Ozesen et al. [35]. The experiments were conducted at the constant engine speed mode (1500 rpm) under the full load condition of the engine. The results showed the slightly lower performance when the engine was run using WPOME or COME compared to diesel fuel. The reason of lowering performance is explained by the lower energy contents of biodiesel fuel. The unburned HC, CO emissions and smoke opacity, decreased by 14.29%, 9.52%, 86.89% with use of the WPOME, decreased by 72.68%, 67.65% and 47.96% with use of the COME, respectively. NO_x emission of WPOME and COME increased by 22.13% and 6.48%, respectively. While the BSFC for WPOME and COME was 7.48% and 6.18% higher than that of diesel.

Kalligeros et al. [43] studied the performance characteristics of a stationary diesel engine fuelled with biodiesel from sunflower oil and olive oil at ratios of 10%, 20%, and 50% by volume of both fuels. They reported that compared to diesel fuel, biodiesel fuel decreased particulate matter due to the higher oxygen

contents in biodiesel, carbon monoxide, hydrocarbon due to fast evaporation and nitrogen oxide emissions due to the higher cetane number of used fuel. Apart from this, volumetric fuel consumption is higher in case of using biodiesel fuel.

Banapurmath et al. [42] studied performance and emission characteristics carried out on a single-cylinder, four stroke, direct-injection CI engine operated with Honge (HOME), jatropha (JOME) and sesame (SOME) oil methyl esters. It has been found that SOME has the highest

Table 4
Work done by various researchers on engine emissions using biodiesel from different sources as the engine fuel.

Biodiesel feedstock	Ref. fuel	Engine	Operating condition	Emission results	Reference
Canola methyl ester	Diesel	1-Cylinder, AC, NA, 4 stroke, DI	Full load and 1800 rpm, 2100 rpm, 2400 rpm, 2700 rpm and 3000 rpm	Lower CO and Smoke but higher NO_x	[58]
Waste palm oil methyl ester and Canola oil methyl ester	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	1500 rpm and full load	Lower CO, HC and smoke but higher NO_x	[35]
Rapeseed oil methyl ester	Diesel	4-Cylinder, WC, NA, 4 stroke, DI	Full load, 1200 rpm and 2400 rpm	Lower CO but higher NO_x	[90]
Lather Industry pre-fleshings	Diesel	4-Cylinder in line diesel engine	Max throttle open and max speed	Lower HC and PM but higher NO_x	[34]
Used cooking oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	1500–3500 rpm	Lower CO but higher NO_x	[44]
Soybean oil methyl ester	Diesel	6-Cylinder, WC, NA, 4 stroke, DI	1400–2600 rpm	CO, CO_2 reduced, NO_x increased	[68]
Used frying oil	Diesel	4-Cylinder, 4 stroke IDI	Maximum speed and full load	CO, HC, PM, CO_2 reduced, NO_x higher	[125]
Rapeseed oil	Diesel	6-Cylinder, 4 stroke, DI	1000–2100 rpm and full load	Lower smoke, CO, HC and higher NO_x	[76]
Soybean, peanut, corn, rapeseed, palm, sunflower, and palm kernel oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	1200 rpm, 1800 rpm and 2400 rpm	Lower smoke, THC and higher NO_x	[32]
Tobacco seed oil	Diesel	4-Cylinder, 4 stroke, WC, TC, DI	1500–3000 rpm	CO, SO_2 decrease and NO_x increase	[71]
Tobacco seed oil	Diesel	4-Cylinder, 4 stroke, WC, TC, DI	50%, 75% and 100% load	CO, SO_2 decrease and NO_x increase	[46]
Waste cooking oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	Different load and 1800 rpm	lower NO_x, PM, HC, higher CO and aldehydes	[75]
Cotton seed, rapeseed, palm soybean methyl ester and waste cooking oil	Diesel	6-Cylinder, 4 stroke, DI, TC	1500 rpm and Part load	Lower HC, CO and Higher NO_x	[36]
Jatropha oil	Diesel	1-Cylinder, AC, NA, 4 stroke, DI	20%, 40%, 60%, 80%, 100% load	HC, CO, CO_2, smoke lower and NO_x higher	[94]
Karanja oil	Diesel	1-Cylinder, NA, 4 stroke, DI	1500 rpm and Part load	HC, CO, smoke lower and NO_x higher	[30]
Waste cooking oil	Diesel	4-Cylinder, 4 stroke, IC, TC, DI	1410 rpm, 1526 rpm, 1743 rpm and 1853 rpm	CO, HC, PM, PAHs reduced and NO_x low difference	[31]
Soy based biodiesel	Diesel	1990 Ford E-350 IDI	Tunnel flow rate 22.3 m3/m used	HC, CO reduced and NO_x Slight difference	[126]
Neem oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	Injection timing set at 130 ATDC	Lower CO, smoke and higher NO_x	[104]
Cotton seed oil methyl ester	Diesel	1-Cylinder, AC, NA, 4 stroke, DI	Full load and 1000–2500 rpm	Lower CO, NO_x, SO_2	[55]
Waste frying oil	Diesel	4-Cylinder, WC, Turbo IC, DI	Full load and 1750–4400 rpm	CO, NO_x reduced but smoke increased	[111]
Karanja methyl ester	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	Different load and 2525 rpm	Lower CO. NO_x and smoke	[59]
Soybean crude oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	Full load and 1500 rpm	Lower CO, HC, NO_x and smoke	[83]
Neem oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	Various load	NO_x, CO, HC and smoke reduced	[105]
Soybean methyl ester	Diesel	4-Cylinder, common rail, TC, DI	2400 rpm and 64 N m load	Lower HC, CO, PM and NO_x	[67]
Mahua oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	At different load	Lower NO_x, HC, CO and smoke	[63]
Polanga seed oil	Diesel	1-Cylinder, 4 stroke, DI	At different load	HC, PM reduced but CO and NO_x increased	[56]
Mahua oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	1500 rpm	NO_x, CO and HC reduced	[74]
Olive and sunflower oil	Diesel	1-Cylinder IDI stationary	At different load	PM, CO, NO_x and HC reduced	[43]
Honge, jatropha and sesame oil	Diesel	1-Cylinder, NA, 4 stroke, DI	1500 rpm	HC, CO, smoke reduced but NO_x slightly higher	[42]
Rapeseed and palm oil	Diesel	4-Cylinder common rail IDI	NEDC driving cycle	Lower NO_x, PM, HC, CO and higher CO_2	[62]
Chinese pistache and jatropha oil	Diesel	1-Cylinder, WC, NA, 4 stroke, DI	1500 rpm and 2000 rpm	Lower NO_x, CO, HC and smoke	[120]
Waste cooking oil	Diesel	4-Cylinder, WC, NA, 4 stroke, IDI	1500–3500 rpm @ 85% throttle	HC, smoke, CO NO_x reduced	[86]
Palm oil	Diesel	4-Cylinder, WC, NA, 4 stroke, IDI	800–3600 rpm @ 50% throttle	Lower HC, CO and NO_x	[127]

AC—Air cooled, WC—Water cooled, NA—Natural aspirates, DI—Direct injection, TC—Turbocharged.

thermal efficiency of (30.4%) compared to 29.51% for HOME and 29% for JOME but lower than diesel (31.25%). Smoke opacity, CO, HC are observed to be higher for SOME, HOME and JOME compared to diesel oil. In contrast to that it was observed that NO_x emissions were higher for diesel operation compared to SOME, HOME and JOME. SOME possesses lower emissions (HC, CO, NO_x) compared to HOME and JOME.

Musthafa et al. [115] studied the effects of biodiesel on nano ceramic Al_2O_3 coated low heat rejection engine using rice bran and Pongamia methyl esters at different loads conditions. Experiments were carried out on single cylinder, four strokes, water cooled, and direct injection diesel engine. It was found that the decrease in SFC was 3.8% for pure diesel, 2.7% for pongamia methyl ester PME100, 5.4% for PME20, 0.7% for rice bran methyl ester RME100, and 8.4% for RME20 in the coated engine (CE) compared with the uncoated engine (UE). Moreover, the increase in thermal efficiency was 8.9% for pure diesel, 7.9% for PME100, 9.9% for PME20, 6.7% for RME100, and 11.3% for RME 20 in the CE compared with the UE. The decreases in HC emission in the coated engine are 41.9% for pure diesel, 55.8% for PME100, 51.2% for PME20, 62.8% for RME100, and 44.2% for RME20. The average decreases in smoke density in the CE compared with the UE are 19.6% for diesel, 28.5% for PME100, and 20.2% for PME20, 25.8% for RME100, and 21.1% for RME20. Increases in NO_x emission in the CE, compared with the UE, are 21.9% for diesel, 16.5% for PME100, 13.2% for PME20, 18.5% for RME100, and 8.2% for RME20. The increases in exhaust gas temperature in the CE, compared with the UE, are 8.7% for diesel, 4.4% for PME100 and 7.5% for PME20, 3.2% for RME100, and 5.9% for RME20. The authors concluded that diesel and biodiesel methyl ester of rice bran and pongamia oil of 20% blend by volume in the diesel fuel may be applied successfully in coated engines, and harmful emissions may be reduced.

Sataynarayana and Muraleedharan [116] studied emission and performance of a diesel engine operated at a rated 1500 rpm using some vegetable oil methyl ester including palm kernel (POB), rubber (ROB) and coconut oil (COB) methyl ester. Among the tested biodiesels and at optimum load (4.1 kW) the maximum efficiency recorded was 37.78% with POB compared to diesel (36.19%). Other biodiesels such as COB and ROB recorded thermal efficiencies 28.04% and 33%, respectively. COB showed less brake thermal efficiency compared to POB and ROB due to high viscosity and low volatility. All biodiesels were exhibiting more CO emission at lower loads and less while at higher loads compared to diesel fuel. The HC emissions were less compared to diesel fuel at all loads. This was attributed to the presence of oxygen molecule in biodiesel motivating complete combustion. It was observed that NO_x emissions were higher for all biodiesels except ROB, compared to diesel fuel operation at all loads.

Bakeas et al. [117] studied the impact of Soy-based biodiesel, palm-based biodiesel and oxidized biodiesel obtained from used frying oils on the regulated and PAH emissions from a Euro 4 light-duty vehicle. The test results show that biodiesel fuel gives higher CO_2 emission and fuel consumption which ranged up to 5%. NO_x emission for all biodiesel fuel except palm biodiesel is higher and it is between 5% and 10%. The emissions of PM, HC, and CO decreased with the addition of biodiesel reaching maximum reductions in the order of 10%, 30% and 20%, respectively. Sharp increases in most PAH, nitro-PAH and oxy-PAH compounds were observed with the application of biodiesel.

McCarthy et al. [118] studied the performance and emissions of a diesel engine fuelled two types of biodiesel (Type A-80% Tallow, 20% Canola oil methyl ester; Type B-70% chicken tallow and 30% waste cooking oil methyl ester) and their blends (B_5, B_{10}, B_{20}, B_{50}, B_{100}). The main findings of this study show that the performance of both bio-diesel fuels reduces with increasing blend ratio, with a torque decrease of 5% for both bio-diesels, and a fuel consumption increase of 7–10%. The reason of that is a lower energy content of biodiesel. However, it was observed that fuel consumption for bio-diesel B is higher than bio-diesel A. Emissions of HC and CO_2 increase with increasing the amount of bio-diesel in their blend, whereas CO emission decreases with increasing the amount of bio-diesel in blend. Biodiesel A shows a decreasing trend with increasing blend ratio while bio-diesel B shows increasing trend with increasing blend ratio for NO_x emission.

Liaquat et al. [119] studied the performance and emission characteristics of a diesel engine fueled with four fuel samples of DF (100% diesel fuel), JB_5 (5% jatropha biodiesel and 95% DF), JB_{10} (10% JB and 90% DF) and J_5W_5 (5% JB, 5% waste cooking oil and 90% DF), respectively, at variable speeds. The test result showed that compared to DF, the three blends of JB_5, JB_{10} and J_5W_5 reduced torque by 0.63%, 1.63% and 1.44% and power by 0.67%, 1.66% and 1.54%, respectively. It was also found that the average increase in BSFC compared to DF was observed as 0.54%, 1.0% and 1.14%, respectively. It was found that at 2300 rpm and 100% throttle position and compared to DF, the average reduction in HC for JB_5, JB_{10} and J_5W_5 was found as 8.96%, 11.25% and 12.50%. Average reduction in CO was 17.26%, 25.92% and 26.87% whereas the reduction in CO_2 was 12.10%, 20.51% and 24.91%. However, some NO_x emissions were increased for all blend fuels compared to DF. In case of noise emission, sound level for all blend fuels was reduced compared to DF. It can be concluded that JB_5, JB_{10} and J_5W_5 can be used in diesel engines without any engine modifications. However, W_5B_5 produced some better results when compared to JB_{10}.

Huang et al. [120] studied the emission characteristic of a diesel engine using Chinese pistache (BDC) and jatropha (BDJ) biodiesel and compared with diesel fuel. They reported that the performance and thermal efficiency of biodiesel is comparable with that of diesel fuel with some increase in BSFC. The results of emission showed that at high loads and at engine speed of 1500 r/min, the CO emissions run by BDJ are 20–25% lower than that run by diesel; for BDC fuel, the CO emissions are 41–60% lower than that run by diesel. Moreover, HC emissions decreased by 17–23% for BDJ and decreased by 17–31% for BDC. NO_x emissions were reported to be 0.3–4.5% less for BDJ and 4.9–9.5% less for BDC. The reduction in smoke emissions is between 8% and 35% for BDJ and 70% and 150% for BDC.

Rakopoulos et al. [121] studied and compared the performance and emission of a direct injection diesel engine operated with various biodiesel fuels and their blend of 10/90 and 20/80 at different load conditions. The main findings of this study showed that biodiesel have almost similar brake thermal efficiency but higher BSFC that of diesel. In case of exhaust emission it was found that biodiesel fuel produces lower CO, smoke and NO_x emission than that diesel.

Gouarieiro et al. [122] studied the emission profile of 18 CC, CO, CO_2, and NO_x emitted by a diesel engine operated using ternary blend (soybean, castor and ethanol) at different speed. The main findings of the study showed all fuel blends emitted more CC than pure diesel. However, no significant difference was observed for CO emission compared to diesel fuel. At 2000 rpm, it was found that the blends reduce CO_2 in the range of 4–6% and NO_x 4–85% compared to (5–24%) and (6.9–75%) at 1800 rpm, respectively.

Ndayishimiye and Tazerout [123] studied the performance and emission characteristics of a diesel engine fuelled with various biofuel blends (palm oil + diesel, palm oil methyl ester and waste cooking oil (WCO) methyl ester). The results show an increasing BSFC (2–25%) with neat preheated palm oil (PO), the PO/diesel fuel blends, and the methyl/ethyl esters of PO + WCO mixture as compared to diesel fuel. The lower heating values and higher densities of those fuels require larger mass fuel flows for the same energy output from the engine, leading to the increase of the brake specific fuel consumption. HC emissions are significantly reduced (30–65%) with preheated palm oil and the methyl/ethyl

esters of PO+WCO mixture as compared to diesel, while they slightly increase when PO/Diesel blends are used. NO_x emissions are found higher with the methyl ester of PO+WCO as compared to neat PO.

Celikten et al. [124] studied the performance and emission characteristics of a diesel engine fuelled with different biodiesel (rapeseed oil biodiesel and hazelnut oil biodiesel) and their blends. It was found that the maximum engine torque and the lowest specific fuel consumption were obtained with diesel. The reason for lower engine performance of biodiesel blends is that biodiesel fuels have lower calorific values and higher viscosity. The exhaust emissions analysis show that the use of biodiesel led to reduction in CO (9.04–15.53%) and smoke (37.18–46.29%) emissions due to the lower sulphur content and higher oxygen contents in the blend compared to that of diesel fuel. However, the biodiesel fuel gives higher NO_x and CO_2 (0.39–2.9%) emissions than diesel fuel due to the higher oxygen contents in biodiesel fuel which improves the combustion efficiency. Table 4 summarized the work done recently by some researchers on engine emissions using biodiesel from different edible and non-edible sources as the engine fuel.

6. Conclusions

The broad range of existing feedstocks for biodiesel production makes biodiesel an important renewable energy source. There are more than 350 oil-bearing crops recognized worldwide as potential sources for biodiesel production. According to some researches, feedstock acquisition currently accounts for over 75% of biodiesel production expenses. The paper provides a comprehensive review on the impact of edible and non-edible biodiesel feedstocks on engine performance and exhaust emissions. According to the analysis of the above literature following summery can be drawn:

- Most of the authors reported that using biodiesel in diesel engines significantly reduce PM, HC, CO emissions, due to higher cetane number, higher oxygen contents compared with diesel fuel. In addition advance injection timing and combustion also favored to lower the total hydrocarbon emissions.
- Most of authors showed that NO_x emissions increase when biodiesel is used in the compression ignition engine. This is occurred due to the higher oxygen contents of biodiesel which results in complete combustion and therefore higher combustion temperature.
- Most of the authors showed that using biodiesel in diesel engines slightly lowered brake power and brake thermal efficiency but increases BSFC than diesel fuel. Higher viscosity, density and lower heating value are the key factors for these issues.

Therefore, it can be concluded that biodiesel production from various feedstocks have potential as a renewable energy source. Biodiesel blended fuel can be substituted of diesel fuel with no or minor engine modification because of offering following benefits:

- Fulfill the energy demand,
- Reduce the dependency on fossil fuel,
- Reduce the pollutant emission load to the environment and adverse effect of fossil fuel on human health.

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